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International spillovers of R&D and marginal social returns

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Abstract
This study analyzes marginal social and private returns of R&D investment through the impact of international spillovers of R&D stocks. We compare the marginal social with marginal private returns using data of 27 OECD and EU countries from 1995 to 2008. We consider two channels of R&D spillovers: embodied in trade flows and disembodied by bilateral technological proximity. We find that marginal social returns on R&D are much larger than the marginal private returns for R&D-intensive countries, in the embodied spillover channel. We also find that the embodied spillover channel through import flows is more important than the disembodied channel.

JEL CLASSIFICATION
E22; O32; O33; O47

1 | INTRODUCTION

The Global Financial Crisis of 2008/2009 has had a serious negative impact on the majority of developed economies. Especially in Europe there is a growing and serious concern for the development of total factor productivity (TFP) growth. Stiglitz (2012) considers the slowdown and uneven distribution of productivity growth as the important cause of the financial crisis. Van Ark et al. (2013) claim that TFP has emerged as the Achilles' heel of Europe's growth performance. This typically applies to the “older” members of the European Union, the EU-15, and maybe less to the accession countries. It is generally believed that investment in R&D could stimulate TFP growth, as it is typically the case for the U.S. economy. Investment in R&D can be transmitted easily by modern IT, leading to international spillovers. On the one hand this could, for instance, lead to a larger growth potential in the EU, where the innovation space has been enhanced, but on the other hand game-theoretic considerations could lead to underinvestment: why should a small open economy invest in R&D if spillovers of investments abroad could be absorbed? In order to understand the role of R&D investment in economic development it is highly relevant to analyze the drivers of investment and, more importantly, the impact of own and imported impact of R&D stocks.

There is a large body of studies that have examined the impact of international spillovers on recipient countries from a variety of angles. Our study is novel in that we estimate the marginal social returns on R&D by incorporating the channels through which a change in the R&D stock of one country is propagated into the R&D activities of other countries. To this end we endogenize the accrual of the domestic R&D stock by estimating R&D investment functions. R&D investment decisions generally depend on the available own domestic R&D stock as well as foreign R&D stocks. Therefore, an exogenous shock to the R&D stock in one country is propagated into the R&D stocks of other countries by way of the interplay of R&D investment across countries. This eventually affects the growth path of all countries. To that end we also estimate the development of TFP. We compute the marginal social returns on R&D investment as well as marginal private returns for each country by estimating this propagation process. To the best of our knowledge, this is the first attempt to estimate marginal social returns on R&D, taking account of the interplay of R&D activities across countries. Specifically, we follow the procedure taken by Bloom, Schankerman, and Von Reenen (2013), who develop a methodology for computing the marginal social and private returns on private R&D capital stocks, measured in terms of the output gains generated by a marginal increase in R&D over heterogeneous firms.

Our sample countries consist of 27 OECD and EU countries during the years 1995 to 2008. Most of the past studies have covered only OECD countries or industrialized countries[1]. Industrialized countries are of course active in R&D investment and to a large extent potential suppliers of technology. We expand the coverage of sample countries to include relatively new EU accession states that the previous studies have not shed light on[2]. These countries are less active in R&D investment, but might benefit more from international R&D spillovers. So the EU accession countries are an ideal set to analyze R&D spillovers in more detail. The World Input–Output Database (WIOD) of the University of Groningen is a perfect database that provides basic data to describe R&D spillovers across borders through bilateral trade flows for all the EU states[3].

Let us preview our main findings. We construct "composite" foreign R&D stocks under two different assumptions of channels through which technology is transmitted across countries. In one channel we assume that imports embody technological knowledge of trade partners and bilateral import shares are used as relative weights of domestic R&D stocks constructing the foreign R&D stock. This is in line with pioneering work of Coe and Helpman (1995). Specifically, we use the total import as weight variables in constructing foreign R&D stocks[4]. In the other channel R&D spillovers are transmitted directly in disembodied form using bilateral technological proximity between countries á la Jaffe (1986).

In our analysis we find that international technology spillovers are better explained by bilateral import shares than by disembodied direct spillovers. The marginal social returns on R&D capital through bilateral import flows are more than twice as large as the marginal private returns for R&D-intensive countries. In contrast, the marginal social returns are slightly above the marginal private returns for less R&D-intensive countries. We also find that the embodied spillover channel is more important than the disembodied spillover channel in the sense that the marginal social returns are much larger than the marginal private returns in the embodied channel. R&D-intensive countries moreover have a larger gap between the marginal social and private returns. It implies that R&D-intensive countries are expected to generate more spillovers at the margin, but the observed R&D is smaller than the—from a global perspective—socially optimal level.

The remainder of the paper is organized as follows. In Section 2 we present a simple model of international R&D spillovers, which serves as a basis to compute the marginal social and private returns on R&D stocks. We describe our dataset and present some descriptive statistics in Section 3. Section 4 shows the results of estimating the TFP functions and R&D investment functions for the countries included. These results form the basis for our simulations that we present by our calibrated estimates of marginal social and private returns in Section 5. The last section concludes.

2 | INTERNATIONAL R&D SPILLOVERS

This section describes the mechanism of international R&D spillovers. Our model is simple and consists of two equations: a production function and an R&D investment function, both of which depend on domestic and foreign R&D stocks[5]. We compute the impact of having an R&D stock in one country on the TFP of other countries, by estimating the R&D investment function wherein a change in R&D investment in one country might affect R&D activities of other countries. The basic intuition is that an R&D stock might be either a complementary or substitutable asset. When the R&D stock of one country is a complement of the R&D stock of other countries, a positive shock of R&D investment in one country will enhance R&D activities of other countries and have a larger effect on TFP of all countries, while the effect of R&D spillovers on TFP will be attenuated if the R&D stock of one country is a substitute of R&D stock of other countries.

2.1 | A model of international R&D spillovers

We assume that there are *N* countries across which technology is spread by way of interplay between R&D stocks. Past studies of international technology spillovers have paid much attention to the channels through which technology is spread across countries. Five channels have been proposed to describe the propagation of technology across borders. One is bilateral import shares. Coe and Helpman (1995) is a pioneering study to estimate the magnitude of international technology spillovers through import flows. Since then import share has been used by quite a few studies such as Lichtenberg and Van Pottelsberghe de la Potterie (1998), Keller (1998), Coe and Hoffmaister (1999), Xu and Wang (1999), Lumenga-Neso, Olarreaga, and Schiff (2005), Lee (2006), Madsen (2007), Zhu and Jeon (2007), Acharta and Keller (2008), and Coe, Helpman, and Hoffmaister (2008). Another case is the bilateral export shares. Funk (2001) finds that exporters receive substantial spillovers from their customers. Third, foreign direct investment (FDI) has been used as a vehicle to transfer international technology. Firm-specific technology is transferred across countries by sharing technology among multinational parents and affiliates. The studies relating technology spillovers to FDI activities are Aitken and Harrison (1999), Globerman, Kokko, and Sjöholm (2000), Xu (2000), Branstetter (2001), Van Pottelsberghe de la Potterie and Lichtenberg (2001), Javorcik (2004), Haskel, Pereira, and Slaughter (2002), Blalock and Gertler (2008), Javorcik and Spatareanu (2008), Keller (2009) and Keller and Yeaple (2009) among others. Fourth, Keller (2002) uses the bilateral geographical distance between countries to measure the magnitude of productivity gains from R&D spending of two countries. Fifth, bilateral technological proximity between countries á la Jaffe (1986) has been used as a weight variable to construct a foreign R&D stock. The studies along this line are Park (1995), Sjöholm (1996), Verspagen (1997), Eaton and Kortum (1999), and Guellec and van Pottelsberghe de la Potterie (2004) among others. See Keller (2004, 2009) for a detailed survey on international technology spillovers.

This issue boils down to the empirical methodology to construct a foreign R&D stock. In general the foreign R&D stock can be expressed as a weighted sum of domestic R&D stocks and its weights reflect the transmission mechanism of technology. We present a detailed explanation about the weights of the foreign R&D stocks in the next section. For the time being we simply state that the foreign R&D stock is a linear combination of each country's domestic R&D stock or,

$$\ln S_i^f = \ln\left(\sum_{j\neq i} \alpha_{ij} S_j^d\right). \tag{1}$$

The logarithm of the foreign R&D stock is approximately written as a linear combination of each country's logarithmic domestic R&D stock. In other words[6]:

$$\ln\left(\sum_{j\neq i} \alpha_{ij} S_j^d\right) = \lambda_i + \sum_{j\neq i} \theta_{ij} \ln S_j^d. \tag{2}$$

We now describe the production structure. The production function is of the Cobb–Douglas type, where gross output is produced by labor, intermediate inputs, the capital stock, the domestic and the foreign R&D stock:

$$\ln X_i = \varphi_0 + \varphi_K \ln K_i + \varphi_L \ln L_i + \varphi_{IM} \ln IM_i + \varphi_1 \ln S_i^d + \varphi_2 \ln S_i^f, (i = 1, \cdots, N), \tag{3}$$

where X_i is gross output of country i, K_i is capital stock of country i at the beginning of the period, L_i is labor input of country i, IM_i is intermediate input of country i, S_i^d is domestic R&D stock of country i at the beginning of period, S_i^f is foreign R&D stock of country i at the beginning of period and N is number of countries.

Substituting Equation 2 into Equation 3 we obtain:

$$\ln X_i = (\varphi_0 + \varphi_2 \lambda_i) + \varphi_K \ln K_i + \varphi_L \ln L_i + \varphi_{IM} \ln IM_i + \varphi_1 \ln S_i^d + \varphi_2 \sum_{j\neq i} \theta_{ij} \ln S_j^d. \tag{4}$$

The R&D investment function is specified as a function of the domestic and foreign R&D stocks, the output growth rate, and debt outstanding or

$$\ln R_i = \mu_0 + \mu_1 \ln S_i^d + \mu_2 \ln S_i^f + \mu_3 \Delta \ln X_i + \mu_4 \ln D_i, \quad i = 1, 2, \ldots, N, \tag{5}$$

where R_i is R&D investment of country i and D_i is debt outstanding of country i.

Substituting Equation 2 into Equation 5 we get:

$$\ln R_i = (\mu_0 + \mu_2 \lambda_i) + \mu_3 \Delta \ln X_i + \mu_4 \ln D_i + \left(\mu_1 \ln S_i^d + \mu_2 \sum_{j\neq i} \theta_{ij} \ln S_j^d\right). \tag{6}$$

We evaluate Equation 6 in the steady state, because we will evaluate the model in its steady state solution. In the steady state, the R&D stock is proportional to R&D investment or

$$S_i^d = \frac{R_i}{\delta}. \tag{7}$$

Moreover, the growth rate of X_i is constant, say g_i in steady state or

$$\Delta \ln X_i = g_i. \tag{8}$$

Substituting Equation 8 and the logarithm of Equation 7 into Equation 6,

$$\begin{aligned}\ln S_i^d &= (\mu_0 + \mu_2 \lambda_i - \ln \delta) + \mu_3 g_i + \mu_4 \ln D_i \\ &+ \left(\mu_1 \ln S_i^d + \mu_2 \sum_{j \neq i} \theta_{ij} \ln S_j^d \right).\end{aligned} \tag{9}$$

When a positive R&D investment shock hits country *i,* it will affect R&D investment of other countries. The sign of μ_2 is important in this respect. When μ_2 is positive, R&D investments of two countries are complements, so that an accrual will enhance R&D activities of other countries. When μ_2 is negative, R&D investments of two countries are substitutes, so that it will decrease R&D activities of other countries. The total change in R&D investment in the steady state is calculated by Equation 9. The total change in R&D investment will in turn lead to a change in total output of not only the *i*th country, but also the other countries via domestic and foreign R&D stocks, as is calculated by the production function, Equation 3.

We define the marginal social returns (MSR) on R&D of country *i* as the increase in gross output of all the countries generated by a marginal increase in R&D stock of country *i*, taking the induced changes in R&D stocks of other countries into consideration. Similarly, the marginal private returns (MPR) on R&D of country *i* are defined as the increase in gross output of country *i* generated by a marginal increase in its own R&D stock[7].

2.2 | Derivation of marginal social returns and marginal private returns

We calculate the MSR_i and MPR_i values from the estimation of the TFP- and R&D-investment equations in the following way.

First, the production function, Equation 4, is written in matrix notation as

$$\ln \mathbf{x} = \boldsymbol{\varphi}_0 + \varphi_K \ln \mathbf{k} + \varphi_L \ln \mathbf{l} + \varphi_{IM} \ln \mathbf{im} + \mathbf{\Phi} \ln \mathbf{s}^d, \tag{10}$$

Where

$$\ln \mathbf{x} = \begin{bmatrix} \ln X_1 \\ \ln X_2 \\ \vdots \\ \ln X_N \end{bmatrix}, \ \ln \mathbf{k} = \begin{bmatrix} \ln K_1 \\ \ln X_2 \\ \vdots \\ \ln K_N \end{bmatrix}, \ \ln \mathbf{l} = \begin{bmatrix} \ln L_1 \\ \ln L_2 \\ \vdots \\ \ln L_N \end{bmatrix}, \ \ln \mathbf{im} = \begin{bmatrix} \ln IM_1 \\ \ln IM_2 \\ \vdots \\ \ln IM_N \end{bmatrix}, \ \ln \mathbf{s}^d = \begin{bmatrix} \ln S_1^d \\ \ln S_2^d \\ \vdots \\ \ln S_N^d \end{bmatrix},$$

$$\boldsymbol{\varphi}_0 = \begin{bmatrix} \varphi_0 + \varphi_2 \lambda_1 \\ \varphi_0 + \varphi_2 \lambda_2 \\ \vdots \\ \varphi_0 + \varphi_2 \lambda_N \end{bmatrix}, \text{and } \mathbf{\Phi} = \begin{bmatrix} \varphi_1 & \varphi_2 \theta_{12} & \cdots & \varphi_2 \theta_{1N} \\ \varphi_2 \theta_{21} & \varphi_1 & \cdots & \varphi_2 \theta_{2N} \\ \vdots & \vdots & \ddots & \vdots \\ \varphi_2 \theta_{N1} & \varphi_2 \theta_{N2} & \cdots & \varphi_1 \end{bmatrix}.$$

Similarly, Equation 9 is written in matrix notation, as

$$\ln \mathbf{s}^d = \boldsymbol{\zeta}_0 + \boldsymbol{\Psi} \ln \mathbf{s}^d + \mu_4 \ln \mathbf{d}, \tag{11}$$

where

$$\ln \mathbf{d} = \begin{bmatrix} \ln D_1 \\ \ln D_2 \\ \vdots \\ \ln D_N \end{bmatrix}, \boldsymbol{\Psi} = \begin{bmatrix} \mu_1 & \mu_2\theta_{12} & \cdots & \mu_2\theta_{1N} \\ \mu_2\theta_{21} & \mu_1 & \cdots & \mu_2\theta_{2N} \\ \vdots & \vdots & \ddots & \vdots \\ \mu_2\theta_{N1} & \mu_2\theta_{N2} & \cdots & \mu_1 \end{bmatrix}, \textit{ and } \ {}_0 = \begin{bmatrix} \mu_0 + \mu_2\lambda_1 - \ln\delta + \mu_3 g_1 \\ \mu_0 + \mu_2\lambda_2 - \ln\delta + \mu_3 g_2 \\ \vdots \\ \mu_0 + \mu_2\lambda_N - \ln\delta + \mu_3 g_N \end{bmatrix}.$$

By total differentiation we obtain the expression of how much a 1% change in the R&D stock of country i induces the changes in each country's R&D stock:

$$\mathrm{d}\mathbf{s}^d = \mathbf{S}_d \,(\mathbf{I} - \boldsymbol{\Psi})^{-1}\, \mathbf{z}^*, \tag{12}$$

where

$$\mathbf{S}_d = \begin{bmatrix} S_1^d & 0 & \cdots & 0 \\ 0 & S_2^d & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & S_N^d \end{bmatrix}, \ \mathrm{d}\mathbf{s}^d = \begin{bmatrix} \mathrm{d}S_1^d \\ \mathrm{d}S_2^d \\ \vdots \\ \mathrm{d}S_N^d \end{bmatrix}$$

and $\mathbf{z}^*$ is an $N \times 1$ vector with one in the ith position and zero elsewhere.

We derive the changes in each country's gross output induced by the changes in all R&D stocks using the production function Equation 10 as

$$\mathrm{d}\mathbf{x} = \mathbf{D}_X \boldsymbol{\Phi} \,(\mathbf{I} - \boldsymbol{\Psi})^{-1}\, \mathbf{z}^*, \tag{13}$$

where

$$\mathbf{D}_X = \begin{bmatrix} X_1 & 0 & \cdots & 0 \\ 0 & X_2 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & X_N \end{bmatrix}, \text{ and } \mathrm{d}\mathbf{x} = \begin{bmatrix} \mathrm{d}X_1 \\ \mathrm{d}X_2 \\ \vdots \\ \mathrm{d}X_N \end{bmatrix}.$$

Then the MSR on R&D of country i is calculated as

$$MSR_i = \frac{(\mathrm{d}\mathbf{x})' \mathbf{z}}{\left(\mathrm{d}\mathbf{s}^d\right)' \mathbf{z}}, \tag{14}$$

where $\mathbf{z}$ is an $N \times 1$ vector of ones.

Similarly, the MPR on R&D of country i is calculated as

$$MPR_i = \frac{(\mathrm{d}\mathbf{x})' \, \mathbf{z}^*}{\left(\mathrm{d}\mathbf{s}^d\right)' \, \mathbf{z}^*}. \tag{15}$$

3 | DATA DESCRIPTION

We take data from the EuroStat database (*EuroStat*), the World Input–Output Database (*WIOD*) and the database of US Patent and Trademark Office (*USPTO*). The first database is used to construct the R&D capital stock series and the second one is mainly used to construct the data on TFP. The second database also provides information on bilateral trade used for constructing the foreign R&D stocks. The third database provides patent data for constructing the foreign R&D stocks based on bilateral technological proximity[8].

The sample period in our study is in principle from 1995 to 2008 and the sample countries are restricted to 27 OECD and "other" European countries (presented in Table A1 in the online Appendix—for access see Supporting Information at the end of the paper). For comparative purpose we show the sample countries in the pioneering work by Coe and Helpman (1995) and Coe et al. (2008).

We construct the R&D stock for the economy as a whole. *EuroStat* provides the time series of nominal R&D expenditures in local currency. Nominal R&D expenditures are converted into real R&D expenditures by the GDP deflator (1995 = 1.00) and further converted to 1995 U.S. constant dollars by the exchange rates of the corresponding countries in 1995. GDP deflators and the exchange rates are taken from the Socio Economic Account of the *WIOD*. The real R&D stocks (in 1995 U.S. constant dollar) are calculated using the perpetual inventory method[9].

Although since the pioneering Coe and Helpman work, a large number of alternative measures of the foreign R&D stocks have been proposed, we limit our discussion to two measures. First there is the import-related measure. The Coe and Helpman study uses bilateral import shares as weights on the premise that imports embody the technological knowledge of trade partners. Lichtenberg and Van Pottelsberghe de la Potterie (1998) suggest an alternative weighting scheme free of aggregation and indexation biases in Coe and Helpman study. Taking the "intensity" of trade into consideration, the Lichtenberg and Van Pottelsberghe de la Potterie study proposes the following measure that is often adopted in empirical studies of inter-industry technology:

$$S_i^{f-LP} = \sum_{j \neq i}^{N} \frac{M_{ij}}{Y_j} S_j^d \tag{16}$$

where M_{ij} is the nominal total imports of country i from country j, Y_j is GDP of country j, and S_j^d is the domestic R&D stock of the jth country. Equation 16 indicates that country i can have access to the fraction of the domestic R&D stock of country j that depends on the ratio of exports from country j to country i to GDP of country j.

The other measure of the foreign R&D stock uses a measure of bilateral technological proximity between countries proposed by Jaffe (1986) as weights of domestic R&D stocks. The Jaffe's proximity measure is defined as

$$\omega_{ij} = \frac{\mathbf{f}_i \mathbf{f}_j'}{\left(\mathbf{f}_i \mathbf{f}_i'\right)^{1/2} \left(\mathbf{f}_j \mathbf{f}_j'\right)^{1/2}}, \quad 0 \le \omega_{ij} \le 1 \tag{17}$$

where $\mathbf{f}_i = \left[\frac{P_i^{TC_1}}{\sum_{z=1}^{T} P_i^{TC_z}}, \frac{P_i^{TC_2}}{\sum_{z=1}^{T} P_i^{TC_z}}, \dots, \frac{P_i^{TC_T}}{\sum_{z=1}^{T} P_i^{TC_z}} \right]$ and $P_i^{TC_z}$ is the number of patents granted to country i and belong to class z of the T technological classes ($z = 1,2, \dots ,T$).

We use the patent-based weights of the past 5-year average to account for possible lags between patent and technology spillovers[10]. The patent data of USPTO are grouped into 475 technological classes or $T = 475$.

The foreign R&D stock of country i is defined as

$$S_i^{f-PT} = \sum_{j \neq i}^{N} \omega_{ij} S_j^d \tag{18}$$

We show the average growth rates of the domestic R&D stock and two measures of the foreign R&D stocks from 1995 to 2008 in Table 1. The average growth rate of the domestic R&D stocks is 4.61%, and the growth rate of the foreign R&D stocks exceeds that of domestic R&D stocks, irrespective of the foreign R&D stock measure. The average growth rate of the foreign R&D stocks ranges from 6.73% (technology proximity measure) to 7.58% (the total import LP measure).

Following the Coe and Helpman study, we estimate an equation for TFP in a logarithmic form as:

$$\ln TFP_{i,t} = \ln X_{i,t} - \varphi_{K,t} \ln K_{i,t-1} - \varphi_{L,t} \ln L_{i,t} - \varphi_{IM,t} \ln IM_{i,t}, \tag{19}$$

where $X_{i,t}$ is real gross output of country i in period t, $K_{i,t}$ is real gross capital stock of country i in period t, $L_{i,t}$ is labor input of country i in period t, $IM_{i,t}$ is intermediate input of country i in period t, and $\varphi_{K,t}$, $\varphi_{L,t}$, $\varphi_{IM,t}$ are cost share of each factor of country i in period t.

All the variables in Equation 19 are taken from the WIOD database. Unit of the variables are millions of 1995 U.S. dollar except for labor input, which is measured in total working hours (in millions of hours). Figure 1 depicts the evolution of ln*TFP* by country[11]. At the beginning of the sample period, 1996, countries are clearly divided into two groups at the value of ln*TFP* that is unity. There are seven countries with ln*TFP* smaller than 1 and 20 countries with ln*TFP* larger than 1. The blue lines are for the high TFP-country group in 1996 and red lines are for the low TFP-country group. The average growth rates of TFP are presented in the fifth column of Table 1. It should be noted that the growth rates are all positive for low TFP countries, while those for high TFP countries sometimes show negative values.

4 | ESTIMATION RESULTS

We estimate both TFP- and R&D-investment functions for 27 countries over the years 1995 to 2008. This time interval is too short to test for panel cointegration, like Kao, Chiang, and Chen (1999) and Coe et al. (2008), in their reexaminations of the econometric foundations of Coe and Helpman (1995)[12].

In Section 3 we have specified the production function as a Cobb–Douglas type. We modify the production function in the estimation so that the dependent variable, the logarithm of aggregate TFP, may be explained by both the domestic (S^d) and foreign stock of R&D investment (S^f):

$$\ln TFP_{it} = \varphi_0 + \varphi_1 \ln S_{i,t-1}^d + \varphi_2 \ln S_{i,t-1}^f + \upsilon_i + u_{it}, \tag{20}$$

where υ_i is a country-specific term and u_{it} is a disturbance term.

TABLE 1 Average growth rates of R&D expenditure, R&D capital stocks and TFP (%)

		(1)	(2)	(3)	(4)	(5)
		R^d	S^d	$S^{f\text{-}LP}$	$S^{f\text{-}PT}$	TFP
Australia	AUS	5.95	5.27	5.42	0.15	−0.12
Belgium	BEL	3.47	3.60	3.55	3.30	−0.67
Bulgaria	BGR	1.65	0.57	14.12	1.94	1.23
Canada	CAN	4.16	4.73	4.91	3.43	0.35
Czech Republic	CZE	5.90	5.79	10.98	37.73	0.68
Germany	DEU	3.25	3.09	3.86	3.19	−1.30
Denmark	DNK	5.36	5.42	6.53	3.38	−0.18
Spain	ESP	7.49	7.28	7.30	3.09	−0.91
Finland	FIN	7.38	7.90	5.46	3.22	−0.38
France	FRA	1.39	1.39	4.30	3.34	−0.06
United Kingdom	GBR	1.97	1.93	5.02	3.30	0.85
Greece	GRC	7.08	6.90	7.92	9.44	2.02
Hungary	HUN	5.71	5.93	13.57	2.58	0.80
Ireland	IRL	7.08	6.86	9.32	4.59	0.17
Italy	ITA	2.90	2.92	4.30	2.65	−0.79
Japan	JPN	2.56	2.44	1.30	3.52	−1.08
Korea	KOR	8.23	7.59	6.15	5.53	−1.24
Latvia	LVA	8.21	7.70	13.41	11.98	1.90
Netherlands	NLD	2.02	2.32	4.37	1.58	−0.14
Poland	POL	4.03	3.47	14.22	5.78	−3.29
Portugal	PRT	10.39	8.74	5.13	7.73	−0.09
Romania	ROU	1.68	−1.31	14.06	9.47	1.69
Slovakia	SVK	−0.22	−1.04	14.74	28.51	0.86
Slovenia	SVN	4.71	3.70	6.74	6.84	−0.45
Sweden	SWE	3.85	4.16	5.50	4.06	−0.13
Turkey	TUR	13.05	13.06	8.52	8.60	1.63
United States	USA	4.07	4.13	3.97	2.71	0.30
Average		4.94	4.61	7.58	6.73	0.06
Standard deviation		3.02	3.16	4.00	8.19	1.16

The foreign R&D stock is measured in two different ways, as explained in the previous section. Equation 20 is estimated by the fixed effects model as well as the random effects model and the preferred model is chosen by the Hausman specification test. It should be noted that we add year dummies to the explanatory variables in the estimation of the models. The first to third columns of Table 2 show the estimation results of the TFP function. The coefficient estimates of the domestic R&D stock are positive and significant in most of the cases. The coefficient estimates of the trade-weighted foreign R&D stocks are significantly positive. The TFP elasticities in terms of the domestic R&D stock range from 0.026 to 0.070 and those in terms of trade-weighted foreign R&D stocks are in between 0.078

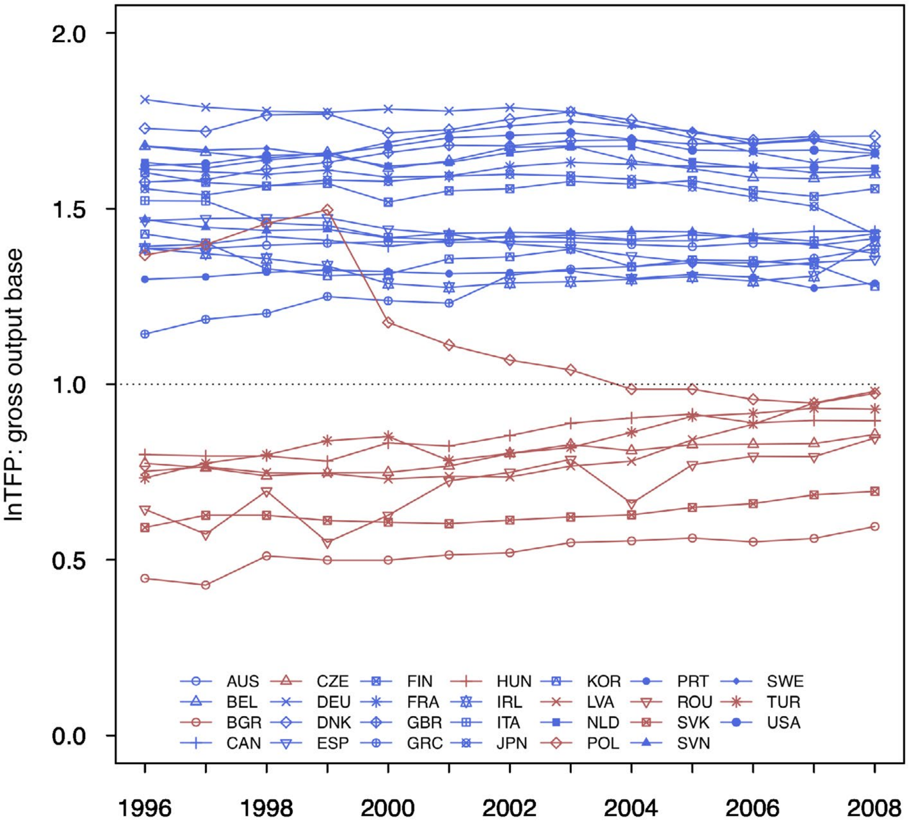

FIGURE 1 Comparison of ln*TFP* over time by country [Colour figure can be viewed at wileyonlinelibrary.com]

TABLE 2 Estimation result of TFP and investment functions

	(1)	(2)	(3)	(4)	(5)	(6)
	TFP function			**Investment function**		
$\ln S^d$	0.070 (4.23)	0.026 (0.95)	0.043 (1.60)	0.742 (14.54)	0.722 (13.72)	0.734 (14.37)
$\ln S^{f\text{-}LP}$	0.093 (5.20)		0.078 (3.66)	0.106 (2.89)		0.176 (4.18)
$\ln S^{f\text{-}PT}$		0.017 (1.67)	0.008 (0.83)		−0.017 (−1.20)	−0.047 (−2.98)
$\Delta \ln X$				0.815 (2.96)	1.118 (4.04)	0.727 (2.56)
$\ln D$				0.387 (8.84)	0.450 (9.72)	0.326 (6.07)
R^2	0.627	0.670	0.620	0.990	0.991	0.990
n	351	347	347	309	305	305
χ^2	2.53	19.93	15.35	40.52	72.55	84.02
	R	*F*	*F*	*F*	*F*	*F*

Note. The figures in parentheses are t values for the fixed effect model and z values for the random effects model. R^2 is the overall coefficient of determination and n is the number of observations. χ^2 is the statistic for Hausman specification test. F and R below χ^2 stand for fixed effect model and random effect model, respectively. Coefficients for time dummies and constant term are omitted to save space.

and 0.093. These values are well within the range of what other studies have reported. The foreign R&D stock based on technological proximity has a significantly positive effect on TFP when it is included as a single indicator of the foreign R&D stock. However, when we include both the trade-weighted foreign R&D stock and the patent-weighted foreign R&D stock together as independent variables, the patent-based foreign R&D stock loses its statistical significance.

The R&D investment function to be estimated is:

$$\ln R_{it} = \mu_0 + \mu_1 \ln S^d_{i,t-1} + \mu_2 \ln S^f_{i,t-1} + \mu_3 \Delta \ln X_{it} + \mu_4 \ln D_{i,t-1} + v_i + u_{it} \tag{21}$$

where v_i is a country-specific term and u_{it} is a disturbance term.

Equation 21 is a standard firm's R&D investment function where R&D investment depends on domestic and foreign R&D stocks at the end of the previous year, the growth rate of gross output (X) and debt outstanding at the end of the previous year (D)[13]. The dependent variable is aggregate real R&D investment. We use the two measures of foreign R&D stocks as independent variables. Year dummies are added to the explanatory variables.

The fourth to sixth column of Table 2 shows the estimation results of the R&D investment function chosen by Hausman specification test. First, the domestic stock has a significantly positive effect on R&D investment in all specifications. Second, output growth rate has a significantly positive effect on R&D investment. Third, debt outstanding has a significantly positive effect on R&D investment. This result indicates that debt outstanding represents a proxy of debt capacity rather than a borrowing constraint. The trade-weighted foreign R&D stock exerts a significantly positive effect on domestic R&D investment. It implies that the domestic R&D investment and the trade-weighted foreign R&D stock are complements. The coefficient estimate of the patent-weighted foreign R&D stock is not statistically significant when it is included as a single indicator of the foreign R&D stock but is significantly negative when both the trade-weighted foreign R&D stock and the foreign R&D stock are used jointly as explanatory variables.[14]

5 | SOCIAL AND PRIVATE RETURNS ON R&D UNDER INTERNATIONAL SPILLOVERS

This section computes the marginal social and private returns on R&D, based on the estimation results of Section 4. We compute the returns on R&D under two different channels through which technology is transmitted across borders. In the first channel technology spillover is embodied in the total import flows. In the second channel technology is transmitted in disembodied form through patent grants in a similar technological space. A comparison of the marginal social returns with the marginal private returns on R&D under different channels of technology spillovers reveals the relative importance of each channel and gives important information—from a global perspective—about the socially optimal level of R&D relative to the observed level. We compute the returns on R&D for the year 2007[15].

In computing the marginal returns on R&D under each channel, we use the coefficient estimates of the domestic and the foreign R&D stocks of the TFP function corresponding to each channel (the first and the second columns of Table 2) and the coefficient estimates of the domestic and foreign R&D stocks of the R&D investment function corresponding to each channel (the fourth and the fifth columns of Table 2).

The ith column of the matrix of $(\mathbf{I}-\mathbf{\Psi})^{-1}$ in Equation 12 gives important information about the extent to which a 1% exogenous change in R&D stock of country i gives rise to changes in the R&D

stock of own and other countries in the steady state in percentage terms. This matrix is an important ingredient to determine the magnitude of R&D spillovers. The matrix $(\mathbf{I}-\mathbf{\Psi})^{-1}$ in the first and second channel is shown in Tables A2 and A3 in the online Appendix , respectively (see Supporting Information). The diagonal elements of this matrix, the own elasticity of the R&D stock change in the steady state, are quite stable across countries, irrespective of the spillover channel. The own elasticity of the R&D stock under the first and second channel is around 3.9 to 4.1 and 3.6, respectively. In other words, a 1% exogenous change in the R&D stock of country *i* eventually raises its own stock by 3.6% to 4.1% in the steady state.

The off-diagonal elements measure the magnitude of spillovers of a change in R&D stocks of one country to the R&D stocks of other countries. In the embodied channel spillover elasticities are positive with the same magnitude, while the spillover elasticities under the disembodied channel are negative with much smaller magnitude. This implies that in the latter case an increase in R&D investment in one country decreases R&D investment of other countries with technological proximity. The spillovers are substantial for countries like Germany, U.S., France, Great Britain, and Japan, regardless of the spillover channel.

Table 3 shows the MSRs (column 2) and MPRs (column 3) for the spillover channel embodied in total imports. The upper panel corresponds to the figures for less R&D-intensive countries and the lower panel corresponds to those for more R&D-intensive countries[16].

The MSRs are much larger than the MPRs for all countries of the R&D-intensive group. In contrast, the MSRs are slightly above the MPRs for the countries of the less R&D-intensive group. The fact that both MSRs and MPRs in the less R&D-intensive group are higher than those in the R&D-intensive group simply reflects a lower level of the R&D stock in the less R&D-intensive group. The average MSR and MPR of the R&D-intensive group are 275% and 120%, respectively and the average MSR and MPR of the less R&D-intensive group are 444% and 421%, respectively. When the magnitude of spillovers is evaluated in terms of elasticities rather than marginal changes, the difference in social and private returns becomes more striking between the more R&D-intensive group and the less R&D-intensive group. There is no discernible difference of the domestic returns in terms of elasticity between the more and the less R&D-intensive group: it ranges from 0.070 to 0.085. However, the average social returns in terms of elasticity for the more R&D-intensive group is 0.181, while that for the less R&D-intensive group is only 0.078.

Table 4 shows the MSRs (column 2) and MPRs (column 3) for the disembodied spillover channel. It is true that the MSRs are larger than the MPRs for all countries of the more R&D-intensive group, while the MSRs are barely above the MPRs for the countries of the less R&D-intensive group, but the ratio of MSR to MPR is 1.66 on average for the more R&D-intensive group. This ratio is much smaller than for the embodied channel. This reflects the much smaller spillover elasticities of R&D stocks under the disembodied channel.

To gauge the relative importance of the spillover channel embodied in trade flows and the disembodied channel from the viewpoint of the magnitude of the MSR, we calculate the MSRs and MPRs, using the coefficient estimates of the TFP function and the R&D investment function where both the embodied and the disembodied channels are taken into consideration at the same time. The embodied spillover channel is evaluated quantitatively by calculating the MSRs and MPRs, based on only the coefficient estimates of the embodied foreign R&D stock in the TFP function and the R&D investment function. Similarly the disembodied spillover channel is evaluated quantitatively by calculating the MSRs and MPRs, based on only the coefficient estimates of the disembodied foreign R&D stock in the TFP function and the R&D investment function. The total effects of both the embodied and the disembodied spillover channels are evaluated quantitatively by calculating the MSRs and MPRs,

TABLE 3 Marginal social and private returns: total import LP measure

	(1) S^d/X (%)	(2) MSR	(3) MPR	(4) MSR (elasticity)	(5) MPR (elasticity)	(6) (2)/(3)
ROU	1.00	6.13	6.93	0.062	0.070	0.88
TUR	1.07	5.88	6.49	0.063	0.070	0.90
BGR	1.15	5.76	6.06	0.066	0.070	0.95
SVK	1.31	4.79	5.31	0.063	0.070	0.90
POL	1.44	4.61	4.86	0.066	0.070	0.95
LVA	1.67	4.19	4.17	0.070	0.070	1.00
GRC	1.83	3.97	3.81	0.072	0.070	1.04
CZE	2.02	4.17	3.49	0.084	0.070	1.20
HUN	2.24	4.08	3.12	0.092	0.070	1.31
PRT	2.29	3.81	3.05	0.087	0.070	1.25
IRL	2.70	3.76	2.60	0.102	0.070	1.45
ESP	2.71	3.39	2.62	0.092	0.071	1.29
ITA	3.21	3.16	2.24	0.101	0.072	1.41
SVN	3.60	3.60	1.94	0.130	0.070	1.86
AUS	4.94	2.57	1.44	0.127	0.071	1.78
BEL	5.15	3.53	1.43	0.181	0.074	2.46
KOR	5.17	2.76	1.46	0.143	0.076	1.89
GBR	5.26	2.67	1.40	0.140	0.074	1.91
NLD	5.79	3.33	1.29	0.193	0.075	2.58
CAN	5.83	2.98	1.31	0.174	0.076	2.27
FRA	6.98	2.52	1.09	0.176	0.076	2.31
DNK	7.35	2.89	0.98	0.212	0.072	2.94
DEU	7.81	2.81	1.08	0.220	0.085	2.60
USA	8.09	1.55	1.04	0.126	0.084	1.49
FIN	8.74	2.82	0.83	0.246	0.072	3.41
JPN	10.43	1.62	0.79	0.169	0.082	2.06
SWE	10.88	2.78	0.69	0.303	0.075	4.05
low S^d/X countries	1.90	4.44	4.21	0.078	0.070	1.12
high S^d/X countries	6.86	2.75	1.20	0.181	0.076	2.40

based on the coefficient estimates of both the embodied and the disembodied foreign R&D stocks in the TFP function and the R&D investment function.

Table 5 summarizes the relative importance of the embodied and the disembodied technology spillover channel. Note that there is not a noticeable difference in MPRs among the embodied channel, the disembodied channel, and the total effects results. However, the MSRs are much larger than the MPRs in the embodied spillover channel and the total effects results. The average ratio of MSR to MPR is 2.32, 1.21, and 2.73 for the embodied, disembodied, and total effects channel, respectively, in

TABLE 4 Marginal social and private returns: technological proximity measure based on patent grants

	(1)	(2)	(3)	(4)	(5)	(6)
	S^d/X (%)	MSR	MPR	MSR (elasticity)	MPR (elasticity)	(2)/(3)
ROU	1.00	2.65	2.55	0.027	0.026	1.04
TUR	1.07	2.53	2.38	0.027	0.026	1.06
BGR	1.15	2.32	2.23	0.027	0.026	1.04
SVK	1.31	2.03	1.95	0.027	0.026	1.04
POL	1.44	1.99	1.78	0.029	0.026	1.12
LVA	1.67	1.59	1.53	0.026	0.026	1.03
GRC	1.83	1.60	1.40	0.029	0.026	1.15
CZE	2.02	1.46	1.27	0.029	0.026	1.15
HUN	2.24	1.38	1.14	0.031	0.026	1.21
PRT	2.29	1.25	1.12	0.029	0.026	1.12
IRL	2.70	1.22	0.95	0.033	0.026	1.29
ESP	2.71	1.20	0.94	0.032	0.026	1.27
ITA	3.21	1.12	0.80	0.036	0.026	1.41
SVN	3.60	0.85	0.71	0.031	0.026	1.20
AUS	4.94	0.73	0.52	0.036	0.026	1.41
BEL	5.15	0.77	0.50	0.039	0.026	1.54
KOR	5.17	0.73	0.49	0.038	0.026	1.48
GBR	5.26	0.80	0.49	0.042	0.026	1.66
NLD	5.79	0.72	0.44	0.041	0.026	1.62
CAN	5.83	0.75	0.44	0.044	0.026	1.71
FRA	6.98	0.67	0.37	0.047	0.026	1.85
DNK	7.35	0.58	0.35	0.043	0.026	1.68
DEU	7.81	0.61	0.33	0.048	0.025	1.89
USA	8.09	0.51	0.31	0.041	0.025	1.63
FIN	8.74	0.45	0.29	0.039	0.026	1.53
JPN	10.43	0.46	0.24	0.048	0.025	1.89
SWE	10.88	0.50	0.24	0.054	0.026	2.11
low S^d/X countries	1.90	1.72	1.54	0.029	0.026	1.15
high S^d/X countries	6.86	0.65	0.41	0.042	0.026	1.66

the R&D-intensive countries. It indicates that the embodied spillover channel is more important than the disembodied one since a positive R&D investment shock in one country induces a large increase in the R&D stock of other countries through trade flows and so generates a much larger output.

To sum up, we obtain two main findings in this section. First, the MSRs on R&D through bilateral import flows are more than twice as large as the MPRs for more R&D-intensive countries, while the MSRs are slightly above the MPRs for the less R&D-intensive countries. Second, the embodied spillover channel through import flows is more important than the disembodied spillover channel in

TABLE 5 Marginal social and private returns with both total import LP measure and technological proximity measure

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
		Total import effect			Patent proximity effect			Total effect		
	S^d/X (%)	MSR	MPR	(2)/(3)	MSR	MPR	(5)/(6)	MSR	MPR	(8)/(9)
ROU	1.00	3.04	4.26	0.71	4.45	4.25	1.05	3.65	4.26	0.86
TUR	1.07	3.03	4.01	0.76	4.26	3.97	1.07	3.62	4.00	0.91
BGR	1.15	2.86	3.72	0.77	3.89	3.71	1.05	3.47	3.72	0.93
SVK	1.31	2.47	3.27	0.76	3.38	3.25	1.04	2.98	3.27	0.91
POL	1.44	2.45	3.03	0.81	3.31	2.96	1.12	2.96	3.01	0.98
LVA	1.67	2.34	2.56	0.92	2.63	2.56	1.03	2.67	2.56	1.04
GRC	1.83	2.33	2.35	0.99	2.62	2.34	1.12	2.70	2.34	1.15
CZE	2.02	2.32	2.18	1.06	2.36	2.12	1.11	2.78	2.17	1.28
HUN	2.24	2.29	1.93	1.19	2.19	1.90	1.15	2.75	1.93	1.43
PRT	2.29	2.26	1.89	1.20	2.02	1.87	1.08	2.62	1.89	1.39
IRL	2.70	2.17	1.64	1.32	1.89	1.58	1.20	2.56	1.62	1.58
ESP	2.71	2.12	1.68	1.26	1.85	1.58	1.18	2.48	1.65	1.51
ITA	3.21	2.02	1.48	1.36	1.66	1.33	1.25	2.37	1.43	1.66
SVN	3.60	2.19	1.20	1.83	1.30	1.19	1.10	2.58	1.20	2.15
AUS	4.94	1.72	0.93	1.84	1.01	0.86	1.17	1.86	0.91	2.04
BEL	5.15	2.15	0.99	2.18	1.02	0.83	1.22	2.56	0.96	2.68
KOR	5.17	1.80	1.04	1.74	1.00	0.82	1.21	1.99	0.98	2.02
GBR	5.26	1.85	0.97	1.90	1.03	0.81	1.28	2.11	0.92	2.30
NLD	5.79	2.10	0.91	2.30	0.91	0.74	1.24	2.48	0.87	2.83
CAN	5.83	1.87	0.93	2.01	0.93	0.73	1.27	2.08	0.89	2.34
FRA	6.98	1.82	0.80	2.27	0.78	0.61	1.28	2.06	0.74	2.79
DNK	7.35	1.94	0.65	3.00	0.70	0.58	1.20	2.22	0.64	3.49
DEU	7.81	1.92	0.89	2.16	0.69	0.54	1.27	2.21	0.81	2.73
USA	8.09	1.27	0.83	1.52	0.61	0.52	1.18	1.13	0.67	1.69
FIN	8.74	1.92	0.55	3.53	0.56	0.49	1.14	2.17	0.53	4.06
JPN	10.43	1.33	0.62	2.14	0.48	0.40	1.19	1.27	0.53	2.42
SWE	10.88	1.92	0.48	4.00	0.49	0.39	1.25	2.19	0.46	4.73
low S^d/X	1.90	2.44	2.61	1.01	2.81	2.57	1.11	2.89	2.60	1.20
high S^d/X	6.86	1.84	0.84	2.32	0.82	0.68	1.21	2.06	0.79	2.73

the sense that MSRs are much larger than the MPRs in the embodied channel. When new technology is embodied in imported goods, it is readily used in production and generates a productivity gain. However, when technology is conveyed through a disembodied patent-weighed R&D stock, it takes time for new technology to be used in the production line and to contribute to productivity growth.

6 | CONCLUDING REMARKS

We examine empirically the extent to which technology is spread across countries by two channels. In one channel technology spillovers are embodied in import flows. In the other channel R&D spillovers are transmitted in a disembodied form of technological proximity. We find that international technology spillovers play an important role in enhancing productivity. Our estimates of the marginal social returns on R&D stocks are higher than the marginal private returns for R&D-intensive countries. We also find that the embodied spillover channel through import flows is more important than the disembodied spillover channel, because the marginal social returns are much larger than the marginal private returns. A large gap between the marginal social returns and the marginal private returns for more R&D-intensive countries implies that R&D-intensive countries are expected to generate more spillovers at the margin, but the observed R&D stock is smaller than the socially optimal level. Policy measures, such as R&D investment credits and subsidies, are therefore needed to enhance R&D activities of R&D-intensive countries. However, R&D externalities deprive recipient countries of R&D spillovers of incentives to invest in R&D activities. Therefore, we should devise international coordination to curb the well-known "prisoner's dilemma" situation and activate R&D investment.

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ENDNOTES

[1]Coe, Helpman, and Hoffmaister (1997) and Seck (2012) are exceptions. They explore the extent to which developing countries benefit from technology spillovers from advanced countries (North–South R&D spillovers).

[2]Relatively new EU accession states in our sample are Hungary, Bulgaria, the Czech Republic, Latvia, Poland, Romania, Slovak Republic, and Slovenia.

[3]See Timmer, Dietzenbacher, Los, Stehrer, & De Vries (2015) for the detailed description of the basic structure of the WIOD database.

[4]Xu and Wang (1999) shows that capital goods trade is a good conduit for R&D spillovers using OECD country data. We also conducted the subsequent analysis, using the foreign R&D stock with the capital goods import as weight variable. It turns out that our main findings remain essentially unaltered. The estimation results are available upon request from the authors.

[5]The model is based upon Bloom et al. (2013).

[6]See Appendix A in the online Supporting Information for a derivation of Equation (2). For access to the Supporting Information, see the end of the paper.

[7]As keenly pointed out in Bloom et al. (2013), the MPR consists of two components. The first is the direct gain in output as a result of increased R&D stock. The second is the output gains through business stealing—a country's R&D advances eventually would manifest in the product market and cause the market share to redistribute. In our analysis country-level

interaction in product market space is not taken into consideration. Omission of the business stealing effect might bias the MPR downward.

[8]It should be noted that the *USPTO* patent database contains only patents that are granted in the United States. Using only U.S. patents might underestimate both the technology similarity and the patent-weighted foreign R&D stock. However, it is not straightforward to aggregate patents granted by different countries since countries adopt different patent classifications. Therefore, we use only the USPTO patent database. The total patent grants in the United States is about a quarter of total patent grants in the world during 1995 to 2008 (WIPO statistics database).

[9]See Appendix B in the online Supporting Information for the detailed procedure to construct the domestic R&D stocks.

[10]The subsequent analysis remains unaltered when we use the patent-based weights with different lag structure.

[11]Our TFP-measure is constructed by subtracting the contribution of labor, capital stock and intermediate inputs from gross output. Most of the past studies use the value-added TFP. We also conducted the subsequent analysis based on the value-added TFP. The results essentially remain unaltered. The estimation results based on the value-added TFP are available on request.

[12]For example, Pedroni (2004) studies the nominal size of the various statistics and shows that at very small values for time dimension ($T = 40$), t statistics for 5% test are somewhat oversized in the range of 10%, whereas the other statistics are somewhat undersized.

[13]Internal funds are also a popular explanatory variable of R&D investment. We also included gross saving as an explanatory variable, but it turns out that it picked up a negative sign.

[14]Bloom et al. (2013) show theoretically that a firm's R&D is positively related to R&D by other firms in the same technology space as long as diminishing returns in knowledge production are not too strong and that a firm's R&D is negatively related to the R&D by other firms in the same technology space when diminishing returns in knowledge production are strong.

[15]Saito and Tokutsu (2015) demonstrate that world trade structure in terms of the international input–output table drastically changed after the Lehman Brothers crisis in 2008 owing to the sharp increase in the export price premium. Therefore, we choose 2007 as a benchmark year to evaluate MSR and MPR.

[16]An R&D-intensive country is defined as the country whose ratio of R&D stock to gross output is above the median of the 27 countries in our sample in the year 2007.

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REFERENCES

Acharta, R. C., & Keller, W. (2008). *Estimating the productivity selection and technology spillover effects of imports* (Working Paper No. 14079). Cambridge, CA: National Bureau of Economic Research. https://doi.org/10.3386/w14079

Aitken, B., & Harrison, A. (1999). Do domestic firms benefit from foreign direct investment? *Evidence from Venezuela. American Economic Review*, *89*(3), 605–618. https://doi.org/10.1257/aer.89.3.605

Van Ark, B., Chen, V., Colijn, B., Jaeger, K., Overmeer, W., & Timmer, M. P. (2013). Recent changes in Europe's competitive landscape and medium-term perspectives: How the sources of demand and supply are shaping up. *European Economy—Economic Papers*, *485*. https://doi.org/10.2765/42628

Blalock, G., & Gertler, P. (2008). Welfare gains from foreign direct investment through technology transfer to local suppliers. *Journal of International Economics*, *74*(2), 402–421. https://doi.org/10.1016/j.jinteco.2007.05.011

Bloom, N., Schankerman, M., & Von Reenen, J. (2013). Identifying technology spillovers and product market rivalry. *Econometrica*, *81*(4), 1347–1393. https://doi.org/10.3982/ECTA9466

Branstetter, L. (2001). *Is foreign direct investment a channel of knowledge spillovers? Evidence from Japan's FDI in the United States* (Working Paper No. 8015). Cambridge, MA: National Bureau of Economic Research. https://doi.org/10.3386/w8015

Coe, D., & Helpman, E. (1995). International R&D spillovers. *European Economic Review*, *39*(5), 859–887. https://doi.org/10.1016/0014-2921(94)00100-E

Coe, D., Helpman, E., & Hoffmaister, A. (1997). North–south spillovers. *Economic Journal*, *107*, 134–149.

Coe, D., & Hoffmaister, A. (1999). *Are there international R&D spillovers among randomly matched trade partners? A response to Keller* (Working Paper No. 99/18). Washington, DC: International Monetary Fund.

Coe, D., Helpman, E., & Hoffmaister, A. (2008). *International R&D spillovers and institutions* (Working Paper No. 14069). Cambridge, MA: National Bureau of Economic Research. https://doi.org/10.3386/w14069

Eaton, J., & Kortum, S. (1999). International patenting and technology diffusion: Theory and measurement. *International Economic Review*, *40*(3), 537–570. https://doi.org/10.1111/1468-2354.00028

Funk, M. (2001). Trade and international R&D spillovers among OECD countries. *Southern Economic Journal*, *67*(3), 725–736. https://doi.org/10.2307/1061461

Globerman, S., Kokko, A., & Sjöholm, F. (2000). International technology diffusion: Evidence from Swedish patent data. *Kyklos*, *53*(1), 17–38. https://doi.org/10.1111/1467-6435.00107

Guellec, D., & Van Pottelsberghe de la Potterie, B. (2004). From R&D to productivity growth: Do the institutional settings and the source of funds of R&D matter? *Oxford Bulletin of Economics and Statistics*, *66*(3), 353–378. https://doi.org/10.1111/j.1468-0084.2004.00083.x

Haskel, J., Pereira, S., & Slaughter, M. (2002). *Does inward foreign direct investment boost the productivity of domestic firms?* (Working Paper No. 8724). Cambridge, MA: National Bureau of Economic Research. https://doi.org/10.3386/w8724

Jaffe, A. B. (1986). Technology opportunity and spillovers of R&D: Evidence from firms' patents, profits, and market value. *American Economic Review*, *76*(5), 984–1001.

Javorcik, B. (2004). Does foreign direct investment increase the productivity of domestic firms? In search of spillovers through backward linkages. *American Economic Review*, *94*(3), 605–627. https://doi.org/10.1257/0002828041464605

Javorcik, B., & Spatareanu, M. (2008). To share or not to share: Does local participation matter for spillovers from foreign direct investment? *Journal of Development Economics*, *85*(1–2), 194–217. https://doi.org/10.1016/j.jdeveco.2006.08.005

Kao, C., Chiang, M.-H., & Chen, B. (1999). International R&D spillovers: An application of estimation and inference in panel cointegration. *Oxford Bulletin of Economics and Statistics*, *61*(S1), 691–709. https://doi.org/10.1111/1468-0084.0610s1691

Keller, W. (1998). Are international R&D spillovers trade related? Analyzing spillovers among randomly matched trade partners. *European Economic Review*, *42*(8), 1469–1481. https://doi.org/10.1016/S0014-2921(97)00092-5

Keller, W. (2002). Geographic localization of international technology diffusion. *American Economic Review*, *92*(1), 120–142. https://doi.org/10.1257/000282802760015630

Keller, W. (2004). International technology diffusion. *Journal of Economic Literature*, *42*(3), 752–782. https://doi.org/10.1257/0022051042177685

Keller, W. (2009). *International trade, foreign direct investment, and technology spillovers* (Working Paper No. 15442). Cambridge, MA: National Bureau of Economic Research. https://doi.org/10.3386/w15442

Keller, W., & Yeaple, S. (2009). Multinational enterprises, international trade, and productivity growth: Firm-level evidence from the United States. *Review of Economics and Statistics*, *91*(4), 821–831. https://doi.org/10.1162/rest.91.4.821

Lee, G. (2006). The effectiveness of international knowledge spillover channels. *European Economic Review*, *50*(8), 2075–2088. https://doi.org/10.1016/j.euroecorev.2005.10.001

Lichtenberg, F., & Van Pottelsberghe de la Potterie, B. (1998). International R&D spillovers: A comment. *European Economic Review*, *42*(8), 1483–1491. https://doi.org/10.1016/S0014-2921(97)00089-5

Lumenga-Neso, O., Olarreaga, M., & Schiff, M. (2005). On 'indirect' trade-related R&D spillovers. *European Economic Review*, *49*(7), 1785–1797. https://doi.org/10.1016/j.euroecorev.2004.06.004

Madsen, J. B. (2007). Technology spillover through trade and TFP convergence: 135 years of evidence for the OECD countries. *Journal of International Economics*, *72*(2), 464–480. https://doi.org/10.1016/j.jinteco.2006.12.001

Park, W. G. (1995). International R&D spillovers and OECD economic growth. *Economic Inquiry*, *33*(4), 571–591. https://doi.org/10.1111/j.1465-7295.1995.tb01882.x

Pedroni, P. (2004). Panel cointegration: Asymptotic and finite sample properties of pooled time series tests with an application to the PPP hypothesis. *Econometric Theory*, *20*(3), 597–625. https://doi.org/10.1017/S0266466604203073

Saito, M., & Tokutsu, I. (2015). Revisiting the "great trade collapse" with the endogenous input-choice model. *Oxford Economic Paper*, *67*(4), 1123–1145. https://doi.org/10.1093/oep/gpv044

Seck, A. (2012). International technology diffusion and economic growth: Explaining the spillover benefits to developing countries. *Structural Change and Economic Dynamics*, *23*(4), 437–451. https://doi.org/10.1016/j.strueco.2011.01.003

Sjöholm, F. (1996). International transfer of knowledge: The role of international trade and geographic proximity. *Weltwirtschaftliches Archiv*, *132*(1), 97–115. https://doi.org/10.1007/BF02707904

Stiglitz, J. E. (2012). *The price of inequality*. New York, NY: W. W. Norton.

Timmer, M. P., Dietzenbacher, E., Los, B., Stehrer, R., & De Vries, G. J. (2015). An illustrated user guide to the world input–output database: The case of global automotive production. *Review of International Economics*, *23*(3), 575–605. https://doi.org/10.1111/roie.12178

Van Pottelsberghe de la Potterie, B., & Lichtenberg, F. R. (2001). Does foreign direct investment transfer technology across borders? *Review of Economics and Statistics*, *83*(3), 490–497. https://doi.org/10.1162/00346530152480135

Verspagen, B. (1997). Estimating international technology spillovers using technology flow matrices. *Weltwirtschaftliches Archiv*, *133*(2), 226–248. https://doi.org/10.1007/BF02707461

Xu, B., & Wang, J. (1999). Capital goods trade and R&D spillovers in the OECD. *Canadian Journal of Economics*, *32*(5), 1258–1274. https://doi.org/10.2307/136481

Xu, B. (2000). Multinational enterprises, technology diffusion, and host country productivity growth. *Journal of Development Economics*, *62*(2), 477–93. https://doi.org/10.1016/S0304-3878(00)00093-6

Zhu, L., & Jeon, B. (2007). International R&D spillovers: Trade, FDI, and information technology as spillover channels. *Review of International Economics*, *15*(5), 955–976. https://doi.org/10.1111/j.1467-9396.2007.00691.x

SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.

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